Cloud, Aerosol and Chemistry Process Research

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Stephen A. Klein

Research Scientist

Lawrence Livermore National Laboratory

PCMDI
Program for Climate Model Diagnosis and Intercomparison

CAPT
Cloud-Associated Parameterizations Testbed

ESGF
Earth System Grid Federation

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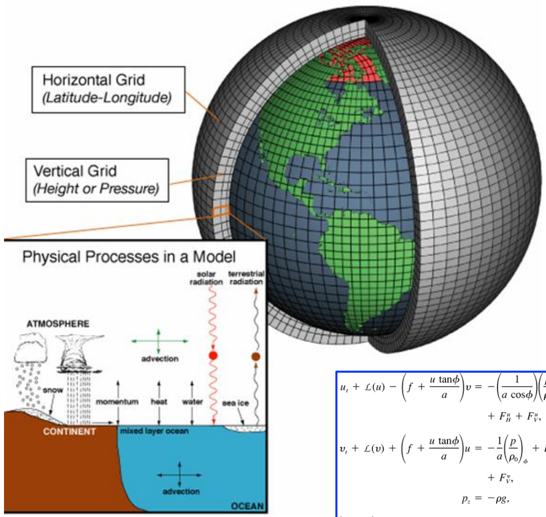
Why Clouds, Aerosols, and Chemistry?

- **Clouds, aerosols, and chemistry are responsible for many of the uncertainties in climate projections**
  - Small changes in clouds can dramatically impact the amount of global warming
  - Emissions of aerosols and chemistry by human activities affect temperatures and air quality

- **Clouds, aerosols, and chemistry are hard to model!**



$$u_t + \mathcal{L}(u) - \left(f + \frac{u\tan\phi}{a}\right)v = -\left(\frac{1}{a\cos\phi}\right)\left(\frac{p}{\rho_0}\right)_\lambda + F_H^u + F_V^u, \quad (1a)$$

$$v_t + \mathcal{L}(v) + \left(f + \frac{u\tan\phi}{a}\right)u = -\frac{1}{a}\left(\frac{p}{\rho_0}\right)_\phi + F_H^v + F_V^v, \quad (1b)$$

$$p_z = -\rho g, \quad (1c)$$

$$\left(\frac{1}{a\cos\phi}\right)[u_\lambda + (v\cos\phi)_\phi] + w_z = 0. \quad (1d)$$

  - The fundamental processes occur at scales much smaller than the resolution of climate models (microns & meters vs. 100 km)
  - The simplified representations are not faithful enough to the true nature of these complex processes

Our Goal: Reducing Climate Projection Uncertainties

- **We aim to improve the representation of clouds and aerosols and chemistry in the DOE-supported comprehensive global climate models (CAM/CESM)**

Activities of LLNL's Cloud, Aerosol, and Chemistry Process Research

Understanding cloud and aerosol processes through DOE (and other) observations

Analyzing cloud feedbacks in model simulations of future climate

Comparing climate model cloud and aerosol simulations to observations

Improving model parameterizations of clouds and aerosols and chemistry

Converting DOE ARM observations into data products usable by climate modelers*

*This effort is funded by the ARM Climate Research Facility and is not being reviewed here today

A Few Notes…

- **For historical reasons, aerosols and chemistry are small part of the effort being reviewed here (<20%) with the bulk of the effort in the area of clouds**
- **Our effort level is approximately 10 Full Time Equivalents, spread over 20 individuals**
- **The effort being reviewed today is spread across several projects and is sponsored by three DOE Office of Science programs:**
  - Regional and Global Climate Modeling Program
  - Earth System Modeling Program
  - Atmospheric System Research Program
- **Rather than compartmentalize my presentation by program or project, I will present the material thematically in order to emphasize the holistic and complementary nature of our effort as well as to emphasize the logic of grouping these activities into a single Scientific Focus Area**

Outline

- **Tools to identify error sources in CAM's simulation of clouds and aerosols**

  CAPT, satellite simulators, and more

- **A phenomenological approach to model problems**

  Diurnal cycle of convective clouds over land, and more

- **A bottom-up approach to model problems**

  Improving cloud, aerosol, and chemical parameterizations in CAM & CESM

- **Cloud feedback research to narrow climate projection uncertainties**

  Quantifying and identify sources of inter-model spread in cloud feedbacks

- **Final remarks**

Tools to identify error sources in CAM's simulation of clouds and aerosols

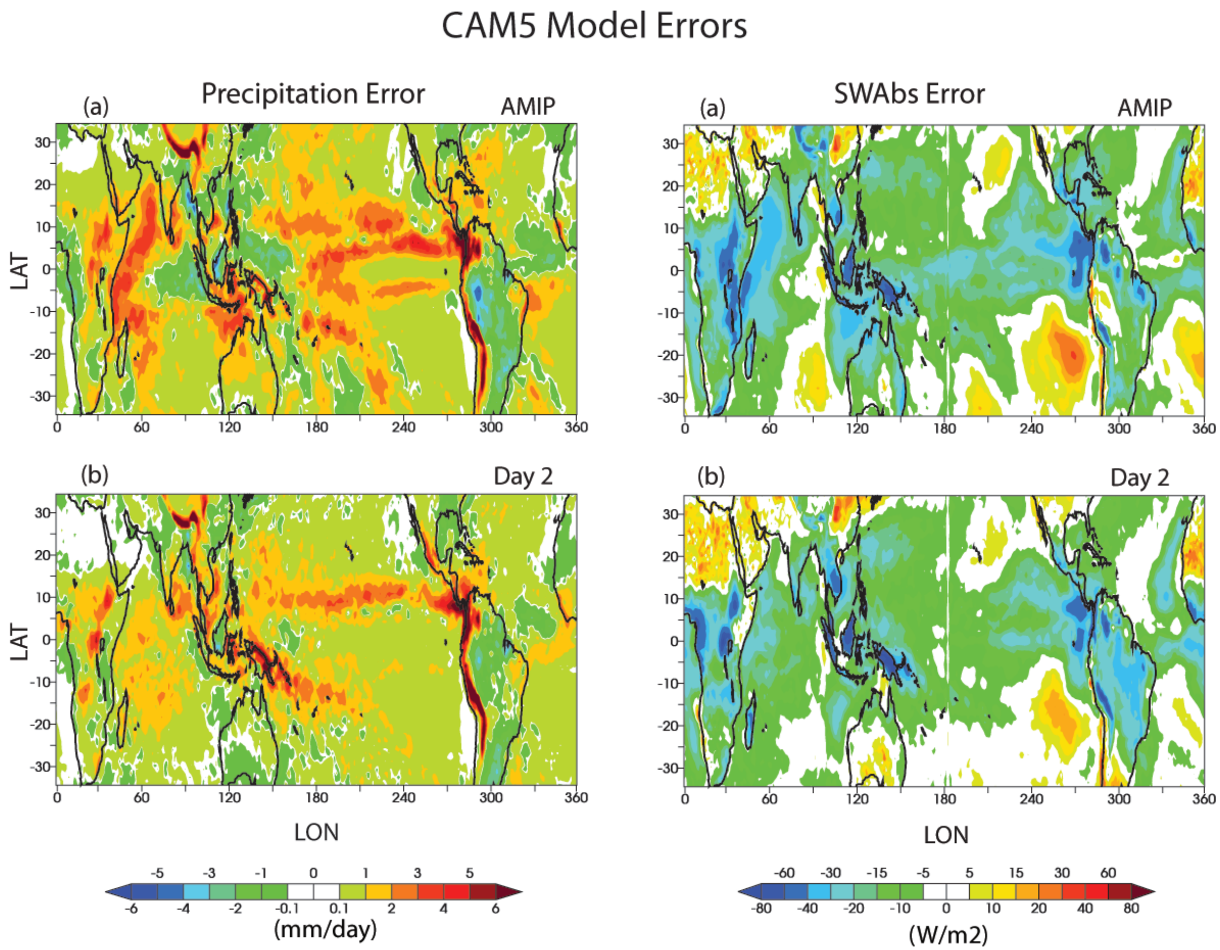
The Cloud – Associated Parameterization Testbed

- **A project of LLNL & NCAR for about 10 years**
- **New parameterizations are tested against ARM (and other) observations**
- **We uniquely integrate climate models in weather-forecast mode**
- **This helps modelers to identify**
  - Simulation errors with ARM data
  - Which parameterizations better simulate cloud and aerosol processes
  - The origin of errors in the simulation of climate
- **Many parameterizations, mainly developed by others, have been tested as a community service**
- **We actively participate in the CAM development process and are an active participant in Atmosphere Model Working Group activities**

Expanding the Scope of CAPT

- **Following encouragement from our 2007 and 2009 reviews, we have expanded our focus to consider simulation quality globally and over longer-time periods**
  - Previously we had focused our attention on field campaigns at ARM sites
- **We performed 6-day hindcasts with CAM4 and CAM5 for every day in the Years Of Tropical Convection (April 2008 – March 2010) period initialized with ECMWF operational analyses**
- **We can systematically examine the correspondence of forecast errors to climate errors**
  - This allows us to separate errors directly resulting from deficiencies in the parameterizations from those due to errors in the large-scale state of the atmosphere, land-surface, or ocean

Many Forecast Errors are Climate Errors



Xie*, *Ma*, *Boyle*, *Klein* and *Zhang *(J. Climate, 2012)*

Other Similarities

- **The vertical profiles of temperature and water vapor biases in the tropical troposphere**
- **Warm biases of surface air temperature over land (cloud problem)**
- **Deficit of shortwave absorption near 60 S (cloud problem)**

Differences

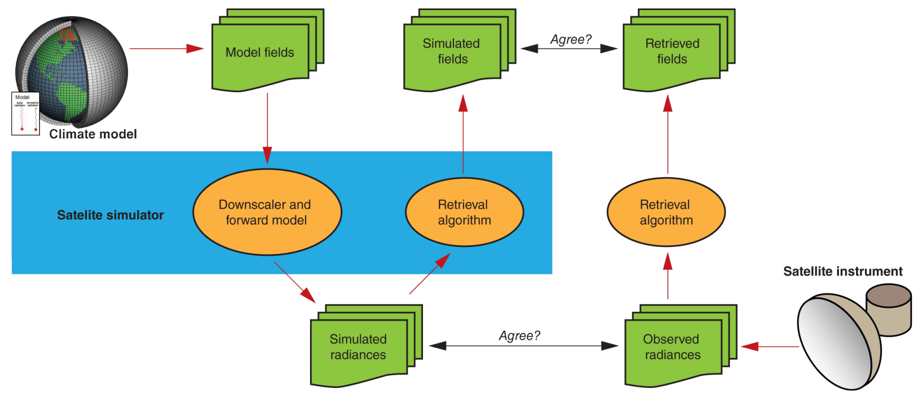
- **Double ITCZ**

See poster by Shaocheng Xie

Effectively Using Satellite Data

- **We have been active developers of the satellite-simulator technique to evaluate clouds in climate models**
- ***What is a satellite simulator?***
  - Diagnostic code applied to model variables to produce output more directly comparable to satellite observations
  - *What would a satellite retrieve if the atmosphere had the model's clouds?*
- **We have contributed the ISCCP simulator and other components to the CFMIP Observation Simulator Package (COSP) which is now used in every climate model and whose output is integral to CMIP/CFMIP**
- **We were major players in importing COSP into the CAM code**

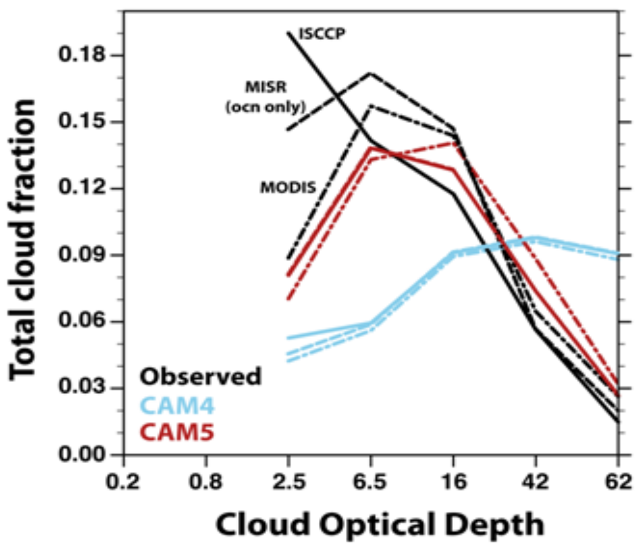
COSP Schematic



*(Bodas-Salcedo and others including **Zhang** and **Klein**, BAMS 2011)*

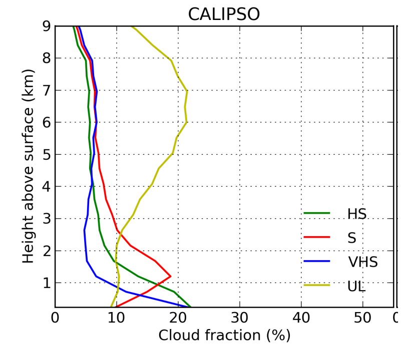
Using COSP in Our Studies

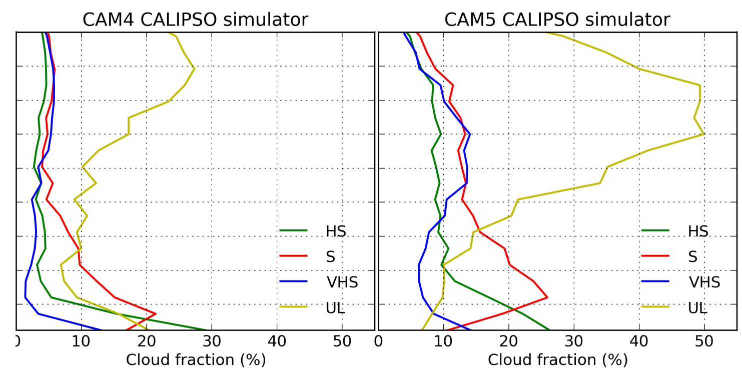
- **CAM5 has a much better representation of clouds even though the regional radiation budget errors are similar in magnitude to CAM4**



*Kay and others including **Zhang**, **Boyle**, and **Klein** (J. Climate, 2012)*

See poster by Neil Barton





***Barton**, **Klein**, **Boyle**, and **Zhang** (JGR, 2012)*

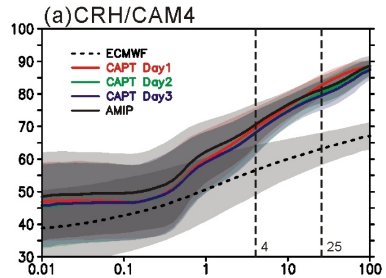
- **Low-level Arctic clouds are much better simulated by CAM5 relative to CAM4 and show the proper response to sea-ice reductions when compared to Calipso lidar observations**

Expanding CAPT's Diagnostic Suite for Rapid Model Assessment

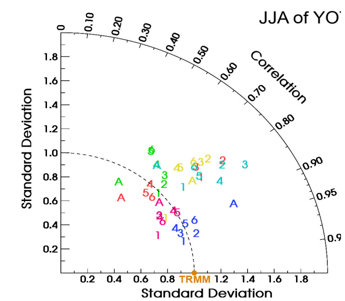
Moist Processes

Tropical precipitation and its relationship with humidity

Column Relative Humidity



Precipitation rate



***Ma** et al. (2012, submitted)*

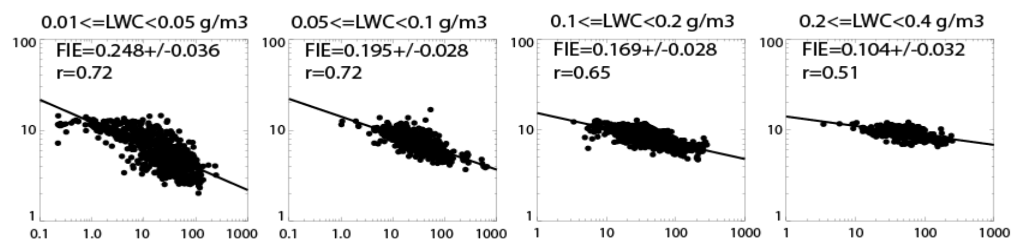
Aerosol-Cloud Interactions

See poster by Cathy Chuang

Relationship of particle size to aerosol

CAM5 at ARM NSA site

Effective Radius



CCN

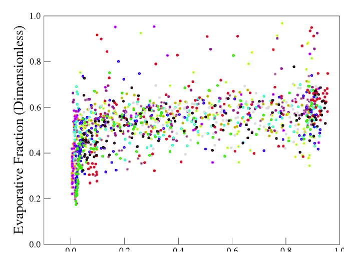
***Zhao**, **Klein**, **Xie**, **Liu**, **Boyle**, and **Zhang** (GRL, 2012)*

Land-Atmosphere Interactions

Relationship of surface fluxes to soil moisture

ARM Observations

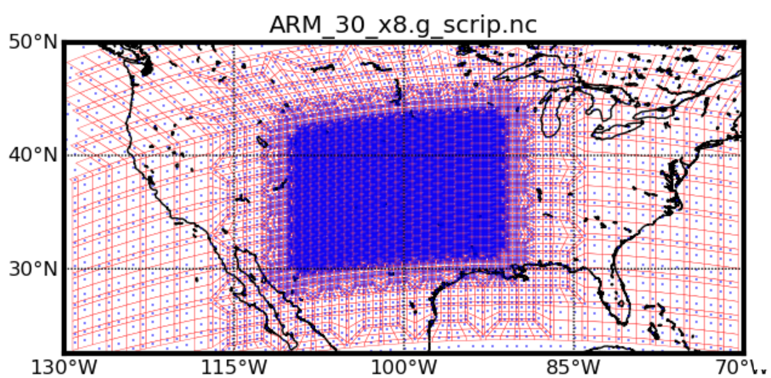
Evaporative Fraction



Soil Moisture Index

Tackling Parameterization Problems at Higher Model Resolutions

- **How do cloud and precipitation simulations change as model resolutions approach 10-30 km?**
- **As part of separate DOE funding (the multi-laboratory CSSEF project), we are developing a CAPT-like testbed utilizing a dynamical core with a regionally-refined grid to efficiently examine model parameterizations in comparison to point (e. g. ARM) observations**

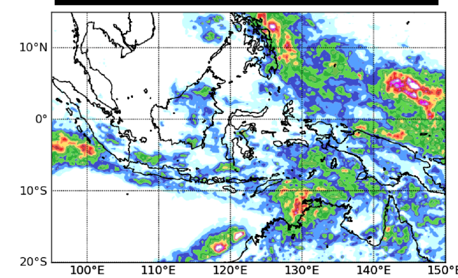


Mark Taylor (SNL), lead developer

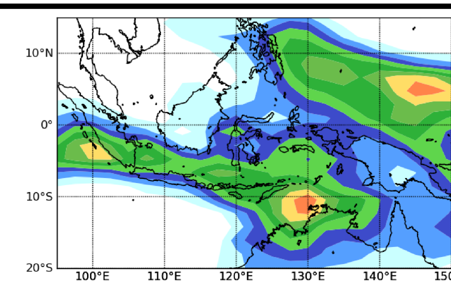
Grid for the global CAM-Spectral Element Dynamical Core with 1/8° resolution over the central U. S. A. and 1° resolution elsewhere

Mean Precipitation
January 20-25, 2006

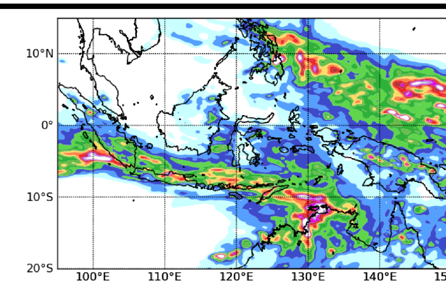
Satellite Observations



CAM3.5 @ 200 km Resolution in CAPT



CAM3.5 @ 30 km Resolution in CAPT

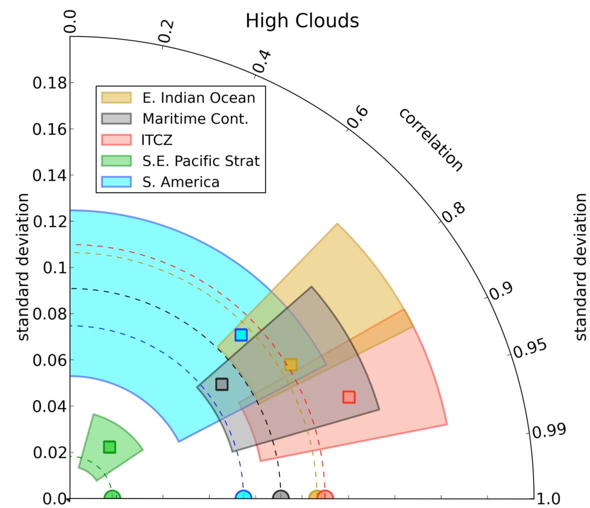


***Boyle** and **Klein** (JGR, 2010)*

Model Sensitivities Explored with Uncertainty Quantification Methods

- **Facilitated by the presence at LLNL of a significant LDRD effort in Uncertainty Quantification, we envision more extensively using Perturbed-Parameter Ensembles to explore the nature of model simulations**
  - Better identify critical parameters
  - Locate structural weaknesses
  - Explore range of tuning sensitivities

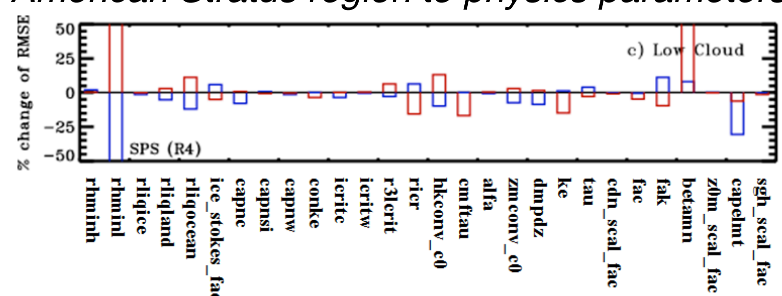
Range of skill in simulating high-level cloud cover in 5 tropical regions from perturbed-parameter simulations



- **We examined how simulated cloud cover in various tropical regions varies with CAM4 physics parameters**

See poster by Yuying Zhang

Sensitivity of low-level cloud cover in South American Stratus region to physics parameters



***Zhang** and others including **Xie**, **Covey**, **Lucas**, **Gleckler**, **Tannahill**, **Doutriaux**, and **Klein** (GRL, 2012)*

A phenomenological approach to model problems

Diurnal Cycle of Convective Clouds and Precipitation Over Land

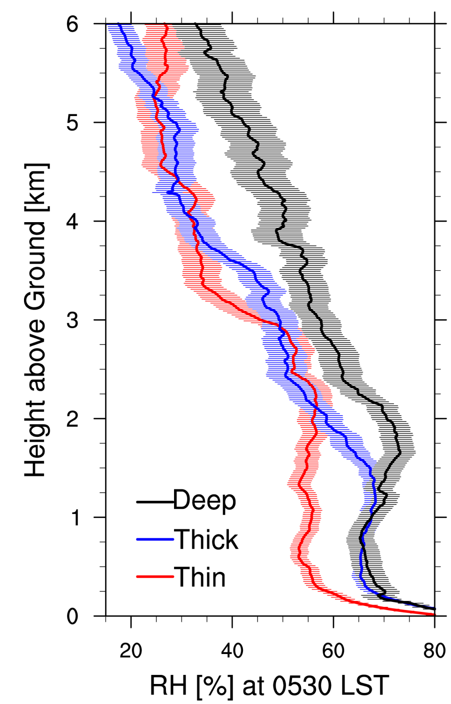
- **The diurnal cycle of convective clouds and precipitation over land is poorly simulated by climate models**
  - Higher resolution (10 km < Δx < 100 km) does not generally solve the problem
- **We used over a decade of ARM Oklahoma observations to determine the factors of the large-scale environment that influence the vertical extent of surface-driven convective clouds**
  - What determines whether shallow convective clouds remain beneath their level-of-free convection (~Δz < 300 m) or penetrate this level and grow to about 1000-2000 m tall?
  - What controls whether shallow convection remains shallow or develops into late-afternoon deep convection?
- **We composited environmental factors for carefully selected days according to categories of cloud development determined by observations from ARM's cloud radar**

?

ARM Observations Provide Critical Tests of Model Simulations

- **Humidity and its vertical profile is the dominant large-scale factor controlling cloud-type selection**
  - This is consistent with the well-known effects of humidity on the buoyancy-reducing effects of entrainment
  - Surface fluxes, vertical stability, wind-shear, boundary layer heterogeneity, and aerosols are secondary
- **We are developing composite forcing cases for Single-Column Models (and LES) in order to test and improve the parameterization of convection in climate models**
  - Better observational constraints than in previous GCSS cases
  - We aim to use new ARM observations of cloud-vertical velocity and 3-D scanning cloud & precipitation radars

Early morning relative humidity for days of thin and thick shallow and deep convection



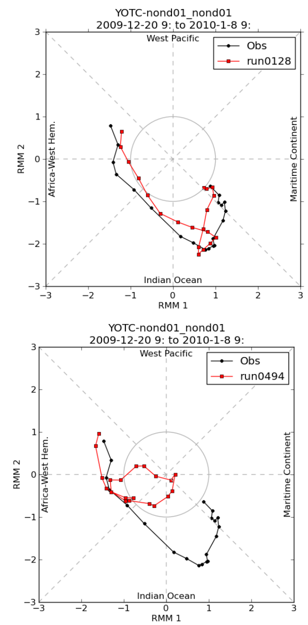
Zhang** and **Klein
(JAS 2010, 2012 submitted)

See poster by Yunyan Zhang

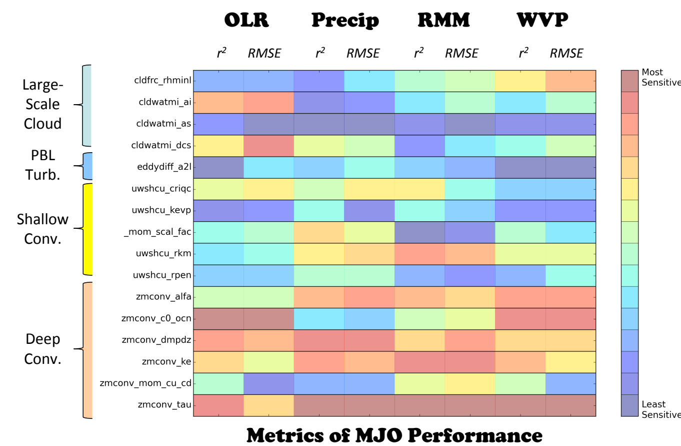
Madden Julian Oscillation and Arctic Low-Level Stability

- **We've exploring the ability of the CAM to simulate the MJO through perturbed-parameter ensembles of 20-day hindcasts of recent strong MJOs**
  - The adjustment time-scale for deep convection is the most sensitive parameter
- **The climate bias of wintertime high-latitude excessive low-level stability is apparent from early in CAPT hindcasts**

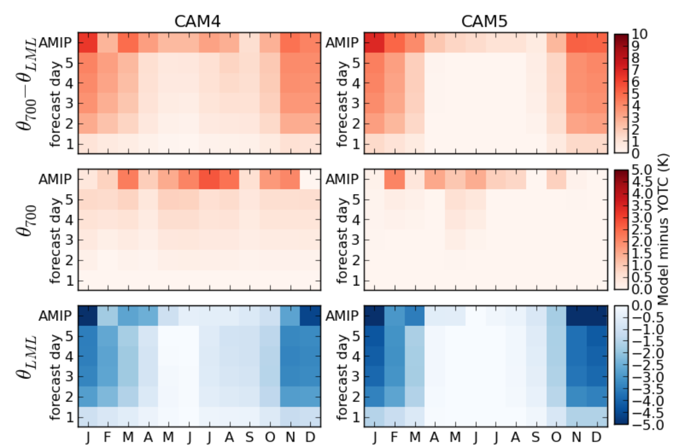
MJO skill in best and worst hindcasts



Sensitivity of MJO metrics to different physics parameters



Biases in CAM4/5 low-level stability and surface and 700 hPa temperature as a function of calendar month and hindcast day

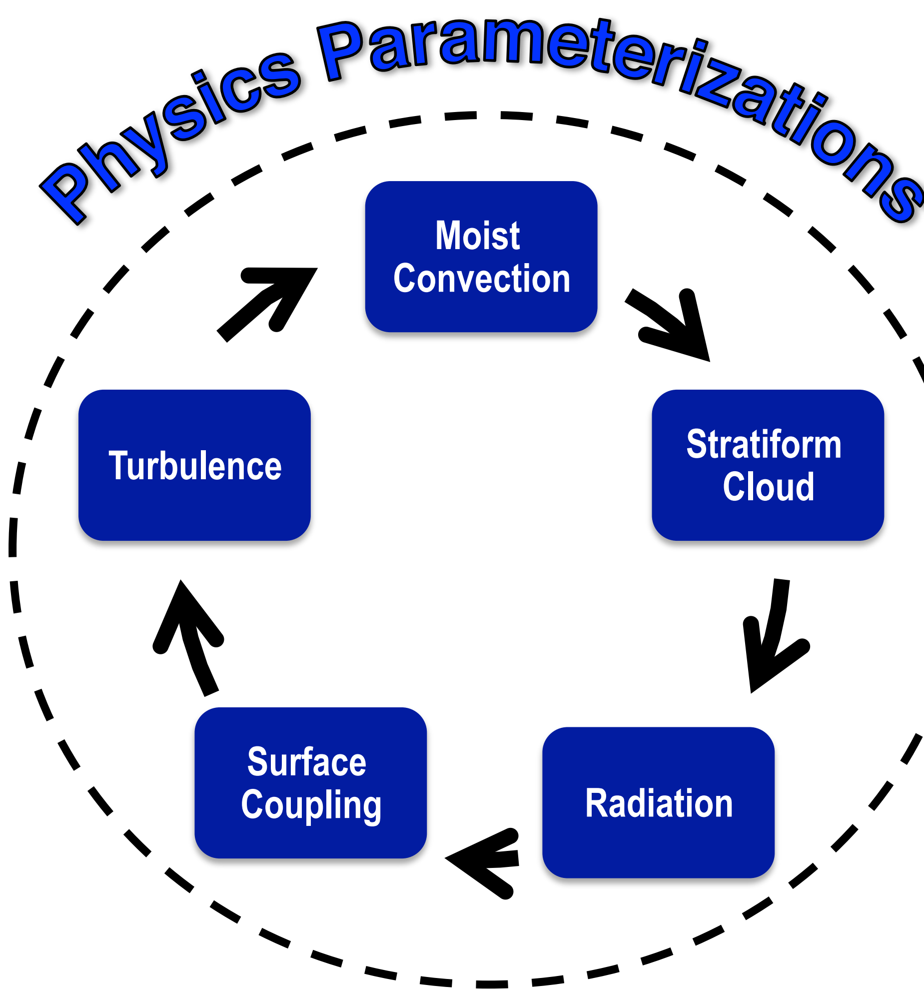


A bottom-up approach to model problems

Improving Cloud Parameterizations by Tackling Process Coupling

- Physical parameterization suites are complicated
- The interactions between processes are understudied and are likely sources of model error
- We have been working to improve the consistency and numerical robustness of CAM's parameterizations

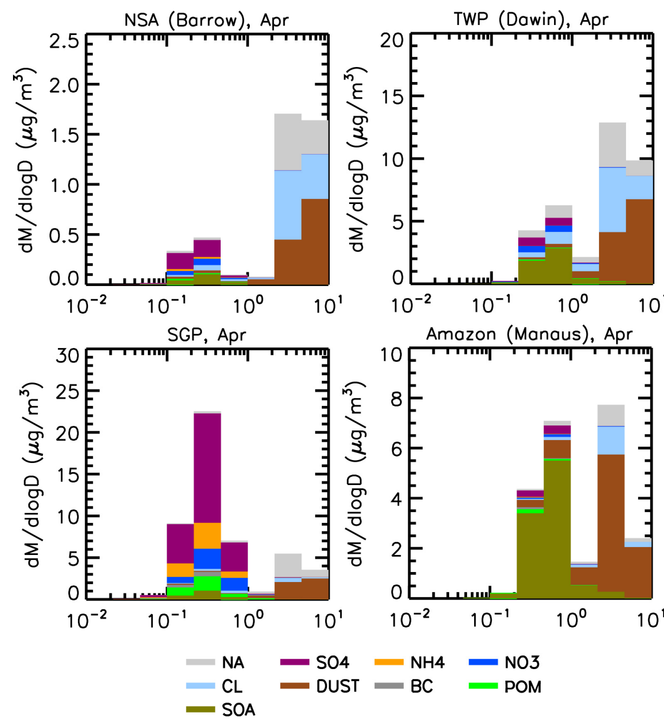
See upcoming talk by Peter Caldwell



What Aerosol Effects are Found with More Complete Representations?

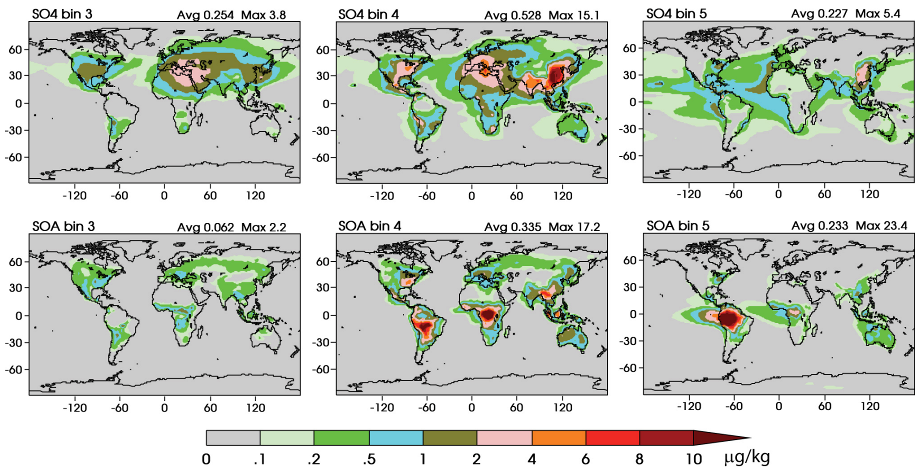
- **Computational constraints limit the ability of climate models to simulate details of the aerosol size distribution and the chemical composition of the Secondary Organic Aerosols (SOAs)**
- **We use a sectional aerosol module (CAM-Sect) to explore effects not considered in CAM's modal aerosol parameterization and potentially develop improvements to the default parameterization**
- **CAM-Sect couples MOZART chemistry with MADRID aerosol microphysics**
  - 210 reactions with 10 reactions for SOA chemistry
  - 111 gas species, 224 aerosol tracers for 26 aerosol species (18 for SOAs) in 8 size bins
  - Improved links of aerosols to their precursor gases and biogenic sources
  - The detailed microphysics potentially improves the representation of aerosol effects on clouds and radiation

Aerosol mass concentrations simulated by CAM-Sect over ARM sites

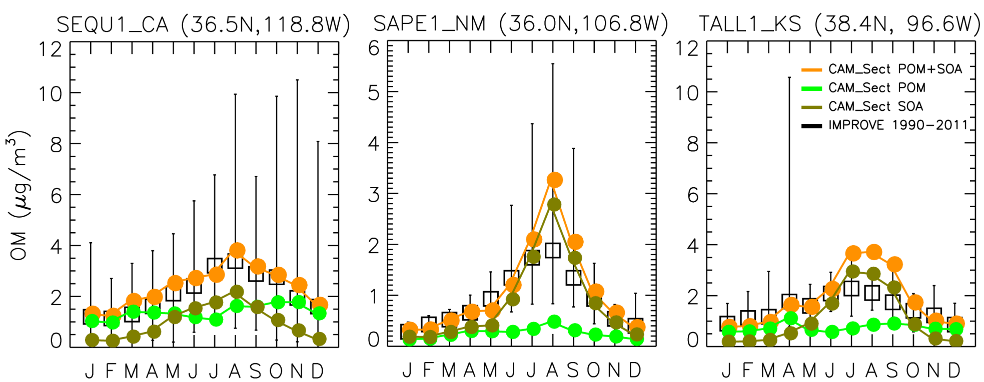


SOAs Comprise a Significant Portion of the Global Aerosol Burden

Surface concentrations of sulfate and SOAs for size bins 3 – 5 (spanning sizes from 0.1 to 1 μm)



Seasonality and magnitude of organic matter at 3 sites over the Western U. S.

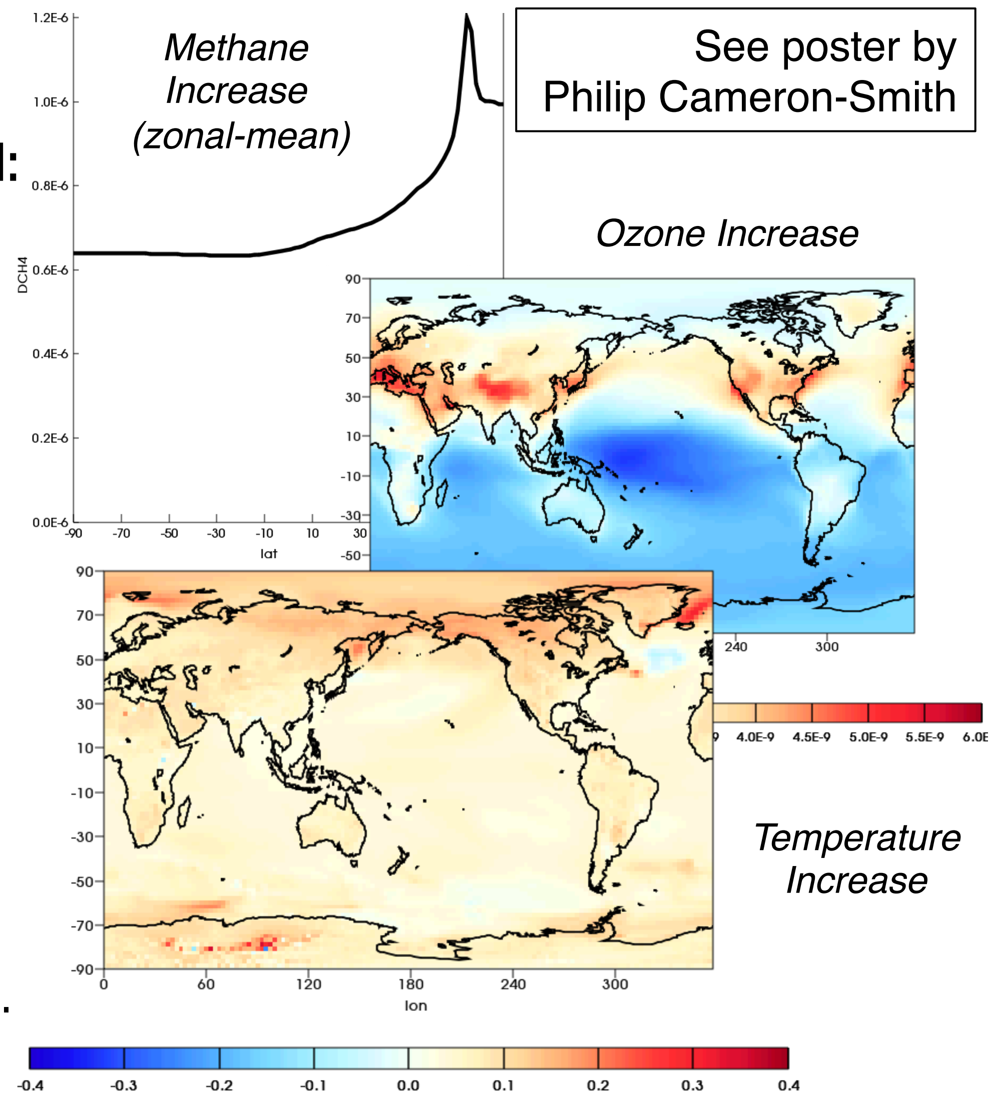


- SOA formation is pronounced in tropical forested areas where there are large biogenic emissions of volatile organic carbon
- CAM_Sect's comprehensive SOA treatment helps to reduce the bias in the spatial and temporal distributions of organic matter particles
- Evaluation of CAM_Sect and investigation of the impact of SOAs on cloud properties are underway

See poster by Cathy Chuang

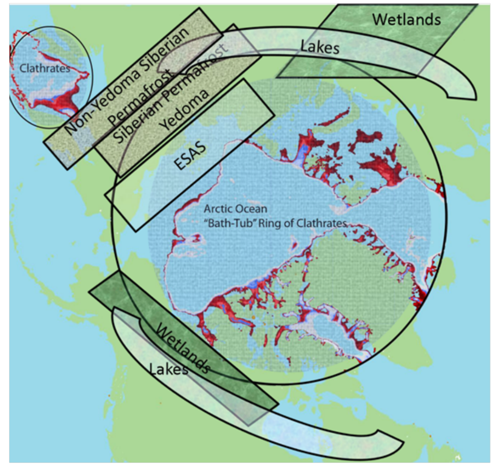
Can a Sudden Methane Release Cause Abrupt Climate Change?

- **Several large methane reservoirs are showing some signs of being released:**
  - Clathrates, permafrost, fracking, etc.
- **We have modified CESM in order to simulate the atmospheric chemistry and climate impacts of a plausible release of methane from oceanic clathrates:**
  - Performed multi-century integrations of a CESM w/ interactive ocean and atmospheric chemistry
  - Non-uniform increases in methane, ozone, and temperature
  - Variability of temperature, ozone, etc. is increased (by ~10-15%)



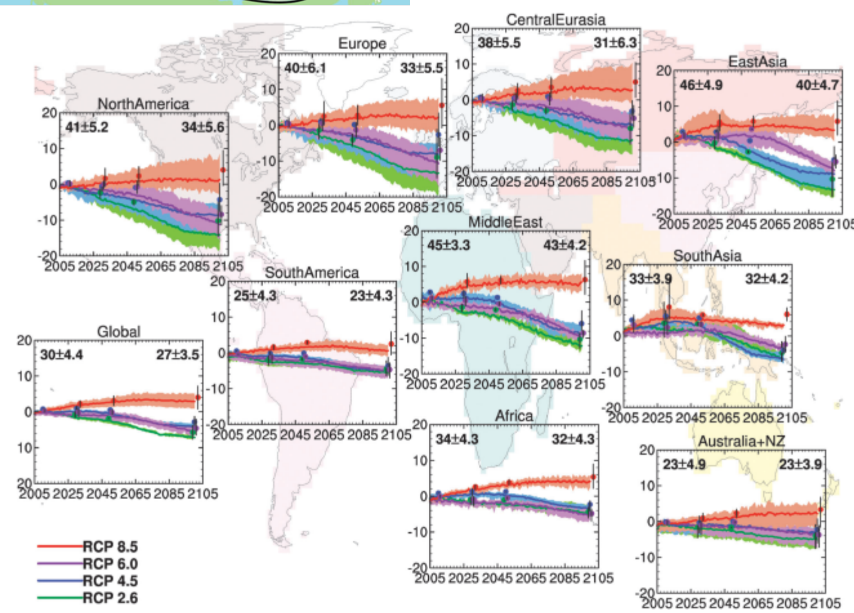
Future Work for Methane and Abrupt Climate Change Research

- **Couple atmospheric methane model to representations of methane in the ocean and permafrost (with LANL and LBNL)**
- **Determine the feedback of warming to emissions (i.e. the methane cycle feedback):**
    - How much extra methane is released from methane-induced warming?
    - How likely is runaway warming?
- **Continue contributions to intercomparisons (e.g., ACCMIP)**



Predicted Sources of Arctic Methane

*Stolaroff and others including **Cameron-Smith** and **Bhattacharyya** (Env. Sci. Tech., 2012)*



Regional Ozone Pollution for RCP scenarios

*Fiore and others including **Cameron-Smith** and **Bergmann**, (Chem. Soc. Rev., 2012)*

Cloud feedback research to narrow climate projection uncertainties

Cloud Feedbacks: A Continuing Problem

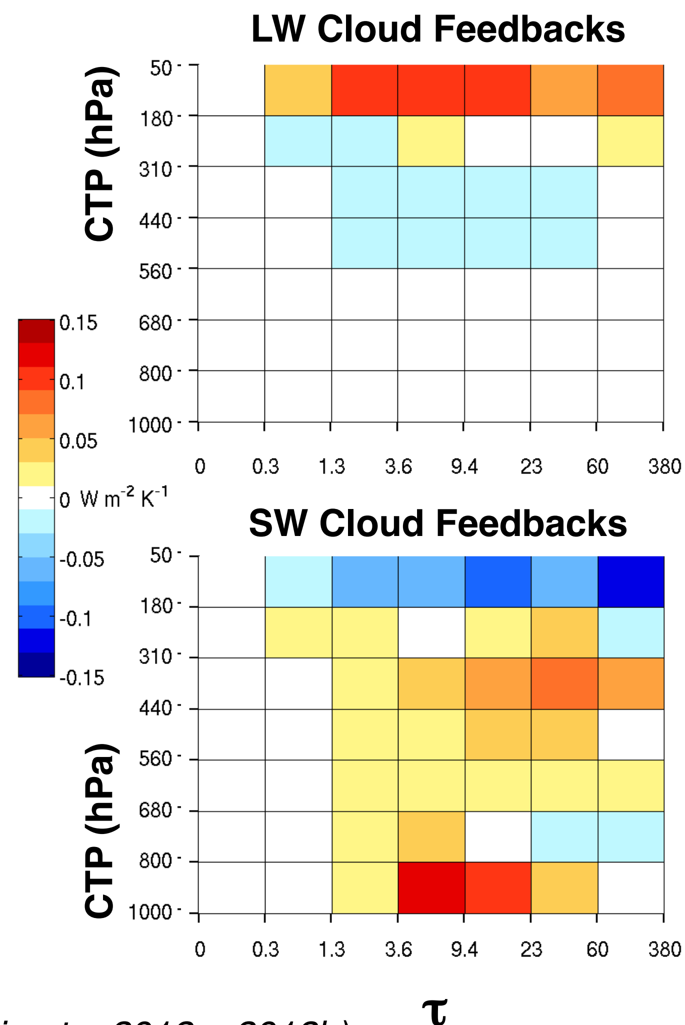
- **How clouds respond to climate change is a largely unsolved problem of high importance for climate science**
- **Improving the ability of models to simulate the clouds of today has *NOT* narrowed the spread of cloud feedbacks**
- **Research is needed to understand:**
  - What physical processes determine cloud feedbacks and whether they are sound
  - What observations can be brought to bear to reduce inter-model spread
- **Since August 2010, LLNL, in partnership with UCLA, has been performing analysis of CMIP3 (CFMIP1) & CMIP5 (CFMIP2) models including:**
  - Quantifying the relative role of different cloud types and cloud responses in producing the global mean cloud feedback
  - Analyzing the sources of inter-model spread in feedbacks from marine stratocumulus, high clouds, and low-cloud optical depths

Quantifying Cloud Feedbacks by Cloud Types

See upcoming talk by Mark Zelinka

- **We've quantified simulated feedbacks according to cloud optical depth (τ) and cloud-top pressure (CTP)**
  - CFMIP ISCCP simulator output and a 'cloud-radiative kernel' are used to calculate the impacts on the top-of-atmosphere radiation budget of clouds in different bins of the CTP-τ histogram
  - We have applied the 'cloud-radiative kernel' to differences in ISCCP simulator output between current and future climate model integrations to yield the first-ever multi-model quantification of cloud feedbacks by cloud type
- **By identifying which cloud types are most responsible for the global mean cloud feedback, we can guide research into the processes determining cloud feedbacks**

CFMIP1 (CMIP3) Global Mean Cloud Feedbacks by Cloud Type

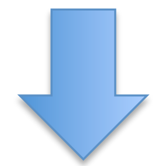


***Zelinka*, *Klein*, and Hartmann (J. Climate, 2012a, 2012b)**

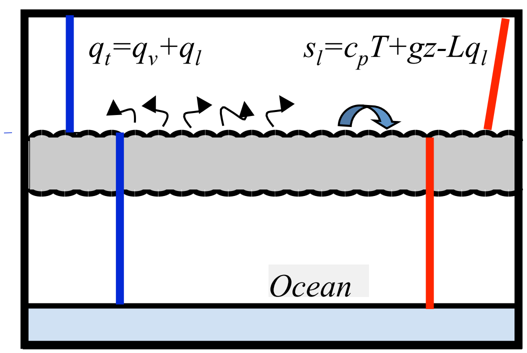
Marine Stratocumulus Cloud Feedbacks

- **We use a stratocumulus mixed-layer model (MLM) driven by boundary conditions from climate models for the 20th and 21st centuries to ask:**
  - How often will stratocumulus occur in the future?
  - How much inter-model spread in cloud feedbacks is due to inter-model spread in physics versus boundary conditions?
- **The MLM predicts that the incidence of subtropical stratocumulus will increase → mainly because the inversion strength (EIS) increases**
- **Climate models robustly predict EIS in stratocumulus regions to increase because temperatures over land and deep convection regions warm relatively more**
- **Inter-model spread in cloud feedback is NOT reduced!**
  - This is largely because the MLM is sensitive to inter-model spread in EIS changes to which climate models are not

CMIP3 Model



Mixed Layer Model (MLM)



Caldwell*, *Zhang* and *Klein
(J. Climate, 2012)

See poster by Peter Caldwell

Marine Stratocumulus Feedbacks

- Can we understand why model predictions differ?
- We test whether a simple heuristic model can explain inter-model variations in the response of low-cloud cover (LCC) in marine stratocumulus regions

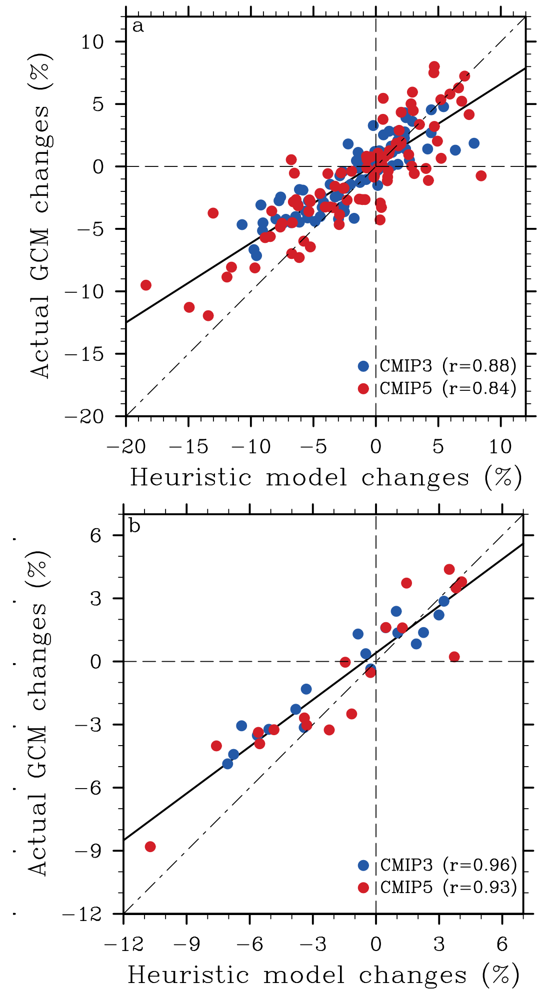
LCC climate change

$$\Delta LCC = \frac{\partial LCC}{\partial EIS}\Delta EIS + \frac{\partial LCC}{\partial SST}\Delta SST + \frac{\partial LCC}{\partial \log(CO_2)}\Delta \log(CO_2)$$

Sensitivity to EIS in current climate

EIS climate change

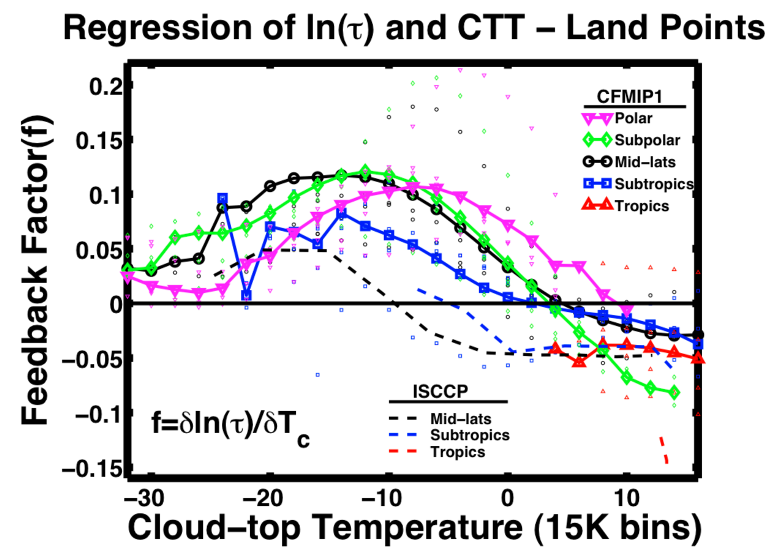
- To the extent that the heuristic model is successful, it suggests that inter-model spread in cloud feedbacks can be reduced through reductions in inter-model spread in
  - the sensitivities of cloud to environmental parameters (particularly SST)
  - how the inversion strength and relative SST change with warming

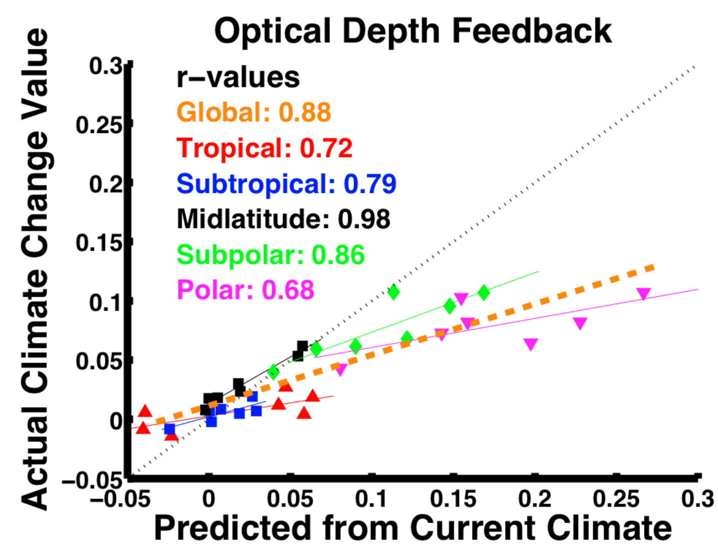


See poster by Xin Qu (Given by Steve Klein)

Can Observations Constrain Low-Cloud Optical Depth Feedbacks?

- **Climate models robustly produce negative cloud feedbacks at high-latitudes due to optical depth (τ) increases (i.e. clouds getting more reflective)**
  - At low-latitudes, τ generally decreases leading to small positive feedbacks
- **Observations have shown similar behavior for the current climate** *(Tselioudis et al. 1992)*
  - Is this potentially an example of time-scale invariance in cloud behavior?
  - If so, can observations be used to constrain this feedback?
- **Our CFMIP1 analysis lends support to these ideas**





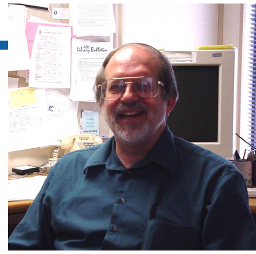
Future Work: Providing Stronger Constraints for Models

- **High-Clouds:** Relate inter-model spread in high-cloud altitude and amount feedbacks to theory and constrain with observations
- **Low-Cloud Optical Depths :** Constrain low-cloud optical depth feedbacks and processes with ARM observations
- **Marine Stratocumulus Clouds:** (a) Determine the physical basis of EIS variations in models; (b) Determine the observational values for the sensitivity of low-level cloud cover to SST (at fixed EIS)
- **Trade-Cumulus Clouds:** Begin work with new UCLA post-doc (Florent Brient)
- **Detection and Attribution of Cloud Trends in Observations:** Ongoing collaboration with Joel Norris (UCSD)

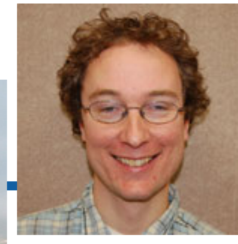
For all of this work, we will fully exploit the unprecedented wealth of cloud diagnostics from CFMIP2/CMIP5: (a) Output of multiple satellite simulators; (b) High-time frequency output from single points; (c) Cloud diagnostics from many experiments

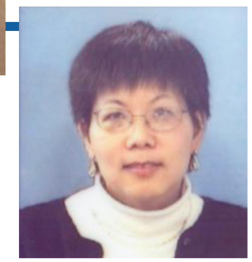
Final Remarks

- **We are making progress in**
  - Diagnosing error sources with advanced techniques
  - Utilizing ARM and satellite data to assess and inform parameterizations
  - Improving CAM simulations of cloud, aerosol, and chemical processes
  - Diagnosing the nature and causes of cloud feedbacks and developing pathways to reduce inter-model spread
- **Thus we believe we are making a positive contribution to reducing climate projection uncertainties due to these processes**
- **We are excited to continued work on these problems!**








Thanks!